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Article

Local changes in snow depth dominate the evolving pattern of elevation-dependent warming on the Tibetan Plateau

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Abstract

Elevation-dependent warming (EDW), whereby warming rates are stratified by elevation, may increase the threat to the life-supporting solid water reservoir on the Tibetan Plateau. Previous studies have debated whether EDW exists and how it is driven. Using temperatures at 133 weather stations on the Tibetan Plateau during 17 different periods generated using a 30-year sliding window over 1973–2018, this study finds that the existence of EDW varies as the period moves forward, and critically it has become more severe over time. During the early part of the record with weaker regional warming, there were limited changes in snow depth and no EDW, but as time advances and regional warming intensifies, snow depth declines significantly at higher elevations, causing development of EDW. We conclude that enhanced regional warming has caused decreases in snow depth, largely controlling the pattern of EDW on the Tibetan Plateau. This may explain contrasting conclusions on EDW from previous studies which have used data for different periods, and our findings support enhanced EDW and more severe depletion of the Tibetan Plateau solid water reserves in a warmer future.

Key words: elevation-dependent warming; Tibetan Plateau; climate warming; snow depth

1. Introduction

The Tibetan Plateau (TP), known as the Earth's Third Pole, is home to the Earth's largest reservoir of solid water outside the polar regions, currently including 10^5 km^2 of glacial extent [1] and 41.9×10^9 m^3 a^{-1} water equivalent of snow [2]. This provides life-supporting water to almost 20% of the world's population [3]. However, most of the reservoir is located at higher elevations, typically above 4000 m on the TP. Increasing evidence suggests that higher elevations may be particularly sensitive to global climate change [4] and strong changes would threaten the solid water reservoir and affect the sustainable water supply downstream [3, 5].

Elevation-dependent warming (EDW), whereby warming rates are stratified by elevation, could mean more rapid change at the critical elevation holding the majority of the solid water reservoir, which in turn would accelerate the rate of ablation of the solid water reserve. EDW on the Tibetan Plateau and its explanatory mechanisms have been intensively studied [4, 6–8]. Early studies used station observations to reveal significant warming on the TP from 1960 to 1990 and find larger warming rates at higher elevations [9]. Subsequently, reanalyses, satellite data and model simulation were employed to elucidate TP EDW and its mechanisms [4]. As satellite records lengthen, remotely sensed data have become more commonly used to examine plateau-wide EDW at high spatial resolution [10, 11]. In addition to investigation of past EDW, future projections can be examined based on regional climate model simulations [12].

Despite extensive study, results from previous studies remain divergent about the existence of Tibetan Plateau EDW [4,6,7]. For example, although clear enhancement of warming with elevation has been observed and simulated from 1960 to 1990 on the TP [9, 13], no EDW was found in another study for 1961–2005 in terms of observations and reanalysis [14]. Recent studies show that warming rates are strongest for the plateau as a whole around 4500–5000 m but weaken again at ultra-high elevations above this [10–12, 15]. Different profiles of warming have also been measured in different mountain ranges on the plateau, based on adjusted MODIS data [16]. In additional to the conflicting observed elevational profiles, the dominant driving factors determining the existence or absence of EDW have also proved elusive [4, 17, 18]. Understanding how the elevation pattern of warming has evolved may help in understanding the driving mechanisms.

Therefore, for the first time, this study tries to understand how EDW may be driven through examining its temporal evolution. Using 133 weather stations across the TP, we examine the elevation profile of warming for different periods using a 30-year sliding window between 1973 and 2018.

2. Materials and Methods

Daily observations of mean 2 m air temperature (°C), total precipitation (mm), snow depth (cm), relative humidity (%), and monthly means of total cloud amount (tenths), and sunshine duration (hours) were obtained from the National Meteorological Information Center, China Meteorological Administration. Daily snowfall is calculated as precipitation which falls when mean daily 2 m air temperature $\leqslant 0$ °C [19]. Snow cover duration is calculated as the total number of days with snow depth >0 cm. The threshold of 0 cm is used to include days with thin snow cover. Original data covered the whole period from 1951 to 2018, but only a few stations have continuous data during the earlier 20–30 years. Thus, we chose 133 stations with elevation >2 km (from over 2400 possible candidates in China) with continuous data for 1973–2018 (Table S1). 2 m air temperatures at a further 420 low-elevation weather stations (0–2 km) within 74–108°E, 22–43°N are also used to represent adjacent lowland warming (Fig. 1).

Observations were previously corrected using a test of spatial consistency [20] and data homogeneity has been assessed using the penalized maximal *t* test [21], *F* test [22] and the standard normal homogeneity test [23]. The amount of missing data is very small (<0.01%). For snow depth, missing records were estimated using daily precipitation and 2 m air temperature. If daily air temperature was below 0 °C, daily precipitation was directly used to convert to daily snow depth, and in the range 0–2 °C, half of daily precipitation was converted to increase the daily snow depth [24]. For other variables, when there were less than 3 consecutive missing values, linear interpolation was used based on the two nearest known values. When more than 3 consecutive values were missing, linear interpolation was based on known values (same day/month as missing value) averaged over the two nearest years. Linear trends of temperature, snow depth, and cloud amount were calculated using the slope of the ordinary least-squares regression line, and statistical significance evaluated using the Student's *t* test method.

3. Results

3.1 Relationships between EDW, mean plateau-wide warming and elevation gradient of snow depth trend

Fig. 1 plots the changing regional warming trend averaged for the 133 stations above 2 km on the Tibetan Plateau compared with that for 420 other stations below 2 km adjacent to the plateau. In both cases a sliding 30-year window is used. Clearly the rate of warming is accelerating in both cases, and the two curves are largely synchronous, meaning that the accelerated warming at high elevations is in part a response to regional atmospheric forcing which is also accelerating warming elsewhere. However, the warming in the plateau is consistently larger. Moreover, the mean plateau-wide warming trend reproduced in Fig. 2 (red hollow circles: left *y* axis) is strongly correlated with the elevation-dependent warming trend (defined as *R*: right *y* axis) over the period of the record. *R* is defined as the correlation between temperature trend magnitude and elevation for stations within the plateau (i.e., over the range 2–5 km). We call *R* for temperature (green solid circles) the internal EDW signal, but *R* can also be calculated for trends in snow depth (blue solid circles). For most of the record the EDW signal for temperature is positive, although in the two early windows this is not the case. Over time, as plateau warming has increased, the EDW signal within the plateau has also increased, and there is a strong correlation (r=+0.88, P<0.001) between the two. The elevation-dependent snow depth trend on the other hand has decreased (i.e., greater decrease in snow depth at higher elevations) over the same time frame and is strongly negatively correlated with the EDW temperature signal (r=−0.96, P<0.001). Because snow depth is decreasing (in contrast to temperature which is increasing), a negative *R* in snow trends (enhanced snow loss at higher elevations) is expected.

In the early part of the record, there was insignificant or even weak EDW with the strongest warming and strongest snow depth declines both at lower elevations, but as time has progressed, both the strongest warming and strongest snow loss have migrated to higher elevations–and they are strongly correlated with each other.

We also examined elevation-dependent relative humidity, sunshine duration, and total cloud cover trends (Fig. S1 online). In most cases the correlations with EDW are weak (P<0.1). Our analysis therefore implies that snow depth change is a dominant driver of the TP EDW signal.

Since snow on the TP is largely absent for half of the year (Fig. S2 online), a seasonal analysis was performed (Fig. S3 online). Unsurprisingly the relationship between EDW, regional mean warming trend on the entire TP, and elevation-dependent snow depth trend is strong in the extended winter (October to May) , but absent (even reversed) in the summer (June to September).

3.2 Impact of snow depth change on EDW

To further examine the impact of snow depth change on EDW, we analyze elevational profiles of snow depth and warming trends during three periods when the correlation between snow depth trend and elevation is most positive (1973–2002), closest to zero (1976–2005), and most negative (1989–2018) (Fig. 3). During the first period (1973–2002), snow showed little change at most elevations, but actually increased above 4 km. At the same time warming was much reduced at the highest elevations. By 1976–2005 both the snow depth trends and temperature trends show almost no gradient with elevation. It is only during the latter period (1989–2018) that snow depth shows the strongest declines at high elevations, coupled with a strong EDW signal.

To more clearly illustrate the relation between the two profiles of warming and snow depth trends, we calculate the differences in temperature and snow trends between the two periods with opposing elevation gradients in snow-change (increasing/decreasing with elevation) (i.e., 1989–2018 minus 1973–2002) (Fig. 4). Significant negative correlations exist between elevational profiles of warming and snow depth trends, suggesting that changes in snow depth are a major influence on changing EDW patterns over time. Decreasing/increasing snow will reflect less/more incoming solar radiation, thus encouraging raising/depression of air temperature through the albedo effect [17].

Taking the above analyses together suggests that during the earlier periods regional warming was relatively weak and did not result in significant changes in snow and EDW. As regional warming has intensified and become statistically significant, snow depth has decreased due to both decreasing snowfall and increased melt (Fig. S4 online). Because the decrease has recently become concentrated at higher elevations, this has been a strong influential factor generating EDW in the most recent period.

4. Discussion and Conclusion

This study reveals that temporal variation in EDW on the TP is significantly correlated with the amplitude of regional mean climate warming. However, it is difficult to conclude that intensified regional climate warming “causes” the EDW or vice versa. We have defined EDW as internal to the TP (i.e., between 2–5 km). One may argue that it is the EDW which has caused the enhanced regional warming on the plateau. However, the fact that the warming on the plateau is in tandem with broader scale warming over the rest of China (Fig. 1) shows that this is unlikely to be the case. It is far more likely that the regional warming is controlled in part by large scale response of the climate system over continental Asia, and that additional EDW has been instilled through local feedback processes which have subsequently resulted (Fig. S5 online).

Regional warming, especially its amplitude, is not immune from local forcing and feedback processes [25]. Radiative forcing by dust and black carbon aerosols from adjacent deserts and local emissions respectively are known to heat the atmosphere over the TP [26], producing excess heat and moisture via the elevated-heat-pump effect [27]. A warmer, moister free atmosphere will also reduce sensible and latent heat exchange from surface to atmosphere and enhance warming of the land surface. Deposition of dust and black carbon will also substantially decrease snow albedo and accelerate snow melt [28]. Regional warming enhanced by these local processes will therefore encourage snow melt and associated EDW. EDW, in turn, accelerates regional warming, causing a positive feedback loop (Fig. S5 online).

This study further reveals that changes in snow depth are a strong control of the variability of EDW during different periods, suggesting that snow albedo is a dominant factor determining the existence of EDW. Changes in snow cover duration (as well as depth) could also correlate with EDW variability because only a relatively thin cover of snow is required to significantly change surface albedo [29]. Further analysis demonstrates this, by showing that the elevation-dependent snow cover duration trend is strongly correlated both with the elevation-dependent snow depth trend (r=+0.93, P<0.001) and the warming trend (r=−0.87, P<0.001) during different periods (Fig. S6 online). Other meteorological factors, such as cloud-radiation, water vapor, wind speed, and sunshine do not show such strong relationships with the existence of EDW. It is the case however that the elevation gradient of relative humidity trends shows a statistically significant correlation with EDW during 1989–2018 (R=+0.67, P<0.01) (Fig. S7 online). This is consistent with the previous findings from Rangwala et al. [30] who have shown that increased humidity has a disproportionate effect on warming at high elevations because the relationship between specific humidity and downwelling longwave radiation is non-linear.

Although this study uses most weather stations that have continuous records on the TP, the results do not represent the western TP well due to an uneven distribution of stations. Intensive field survey and more observations are required in the western TP to examine EDW there in future. Owing to high resolution and regional coverage, remotely sensed platforms have much potential to examine EDW on the TP [31]. MODIS now has around 20 years of land surface temperature (LST) data and has been demonstrated to be potentially reliable [11, 16]. More studies need to calibrate such remotely sensed data sources against in situ observations so that the former can offer opportunity to quantify EDW in the western TP.

In conclusion, this study reveals that the amplitude of regional climate warming determines the existence of EDW on the TP. Changes in snow depth, usually concentrated at higher elevations, act as a bridge to connect regional climate warming and the existence of intra-plateau EDW. Our findings help to explain why there is divergence in previous studies about the existence of EDW and its associated mechanisms. It also has critical implications for the Tibetan Plateau solid water reserves, implying quicker ablation in a warmer world.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgment

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Author Contributions

Donglin Guo developed the original idea. Donglin Guo, Kun Yang, Nick Pepin designed the study. Duo Li led the data compilation and Donglin Guo performed statistical analyses. Donglin Guo and Nick Pepin led the preparation of the manuscript with contribution from all the authors. All authors discussed the results and reviewed the manuscript.

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Figure captions:

Figure 1. Evolution over time of mean warming on the TP and surrounding lowlands. (a) Location of the selected weather stations with different elevations (common color bar showing elevation). (b) Comparison between mean warming trends for different groups of stations; all stations (*n*=553), stations on TP (elevation > 2 km: *n*=133), and surrounding lowland stations (elevation ≤ 2 km: *n*=420). The correlation coefficient (*r*) between mean warming trends for stations on the TP and surrounding lowland stations is

given in the top left corner of (b).

Figure 2. Relationship of the entire Plateau-mean warming trend (red hollow circles, left *y* axis) with elevation-dependent warming trends (*R*, right *y* axis, green solid circles) and elevation-dependent snow depth trends (*R*, right *y* axis, blue solid circles) for different periods across selected 133 weather stations with elevation > 2 km. *R* is defined as the correlation between warming/snow depth trend magnitudes and elevation for stations within the plateau (i.e., over the range 2–5 km). Correlation coefficients (*r*) of elevation-dependent warming trends (green solid circles) with the entire Plateau-mean warming trend (red hollow circles) and elevation-dependent snow depth trends (blue solid circles) are given. The two dashed horizontal black lines represent the critical *R* value (±0.17, right *y* axis) at statistical significance $P<0.05$. The labels "{1}", "{2}", "{3}" denote the three periods that have the most positive (1973–2002), closest to zero (1976–2005), and the most negative (1989–2018) *R* between snow depth trend and elevation.

Figure 3. Elevational profiles of snow depth trends and air temperature trends for the three periods when the correlation coefficient between snow depth trend and elevation is most positive (1973–2002) (left), closest to zero (1976–2005) (middle), and most negative (1989–2018) (right), also indicated by labels "{1}", "{2}", "{3}" in Fig. 2.

Figure 4. Elevational profiles of the difference in snow depth and air temperature trends between 1989–2018 and 1973–2002. The black dashed lines represent the regression line matched by a regression equation. The correlation coefficient (*r*) between snow depth and air temperature trends is

given in the middle of the figure. The numbers on the top of the figure are the number of weather stations in the corresponding elevation bin.

Donglin Guo is a professor at the Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences. He is engaged in land-atmosphere interaction, with a focus on land surface process simulation, frozen ground simulation and climate change.

Graphic abstract:

Climate change is having disproportionate impacts on the Tibetan plateau. Elevation-dependent-warming (EDW), faster warming in high mountains, poses an enhanced threat to life-supporting snow/ice reserves above 5000 m. Past studies debate how EDW is caused, and cannot predict how it will change in future. This study, for the first time, shows that the amplitude of regional warming determines the pattern of EDW, and that changing elevation gradients in snow depth over time have been responsible. Snow loss at increasingly higher elevations moves the zone of enhanced impact uphill, probably continuing in future. Our results explain the divergence in previous studies about causes of EDW, and also have critical implications for longer-term sustainability of water resources on the Tibetan Plateau.